

# Laser Retroreflectors for Didymos, Comets, Phobos, Deimos, CLPS and Lunar Lagrangian L1 for Exploration, Planetary and Gravity Sciences

NASA Exploration Science Forum, NASA-ARC, July 23, 2019



**Jet Propulsion Laboratory**  
California Institute of Technology  
Pasadena, California



**INFN**  
Istituto Nazionale  
di Fisica Nucleare  
Laboratori Nazionali di Frascati

**SCF\_Lab**  
Satellite/Lunar/GNSS  
laser ranging/altimetry and Cube/microsat  
Characterization **F**acilities **L**aboratory

The SCF Lab logo features a stylized globe with a rainbow spectrum, and the text 'SCF Lab' and 'INFN' around it.

## USA-Italy Program => ASI-INFN Association-Affiliation to NASA-SSERVI

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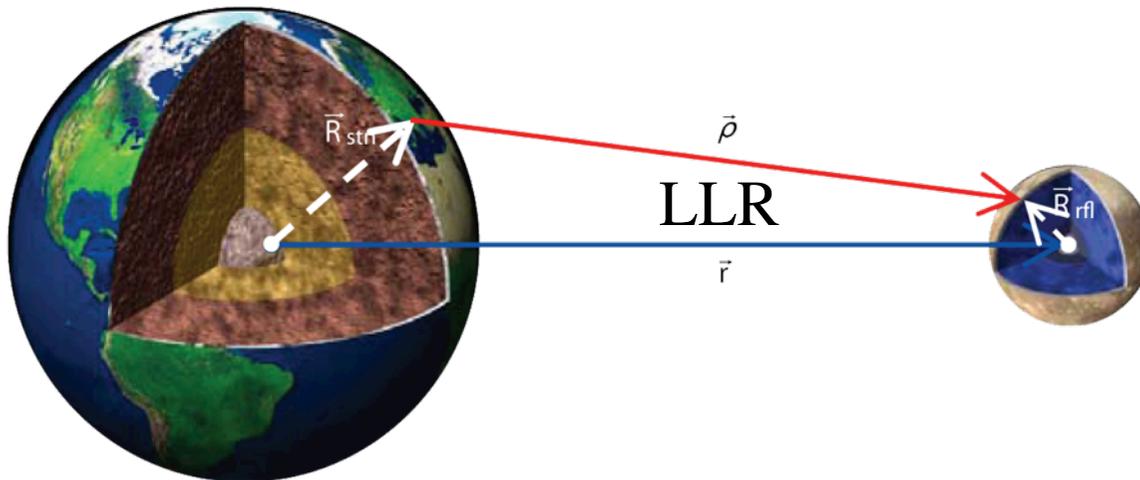
<sup>11</sup>*NASA–Ames Research Center (ARC), CA, USA*

(underlined authors collaborate on Martian laser retroreflectors)

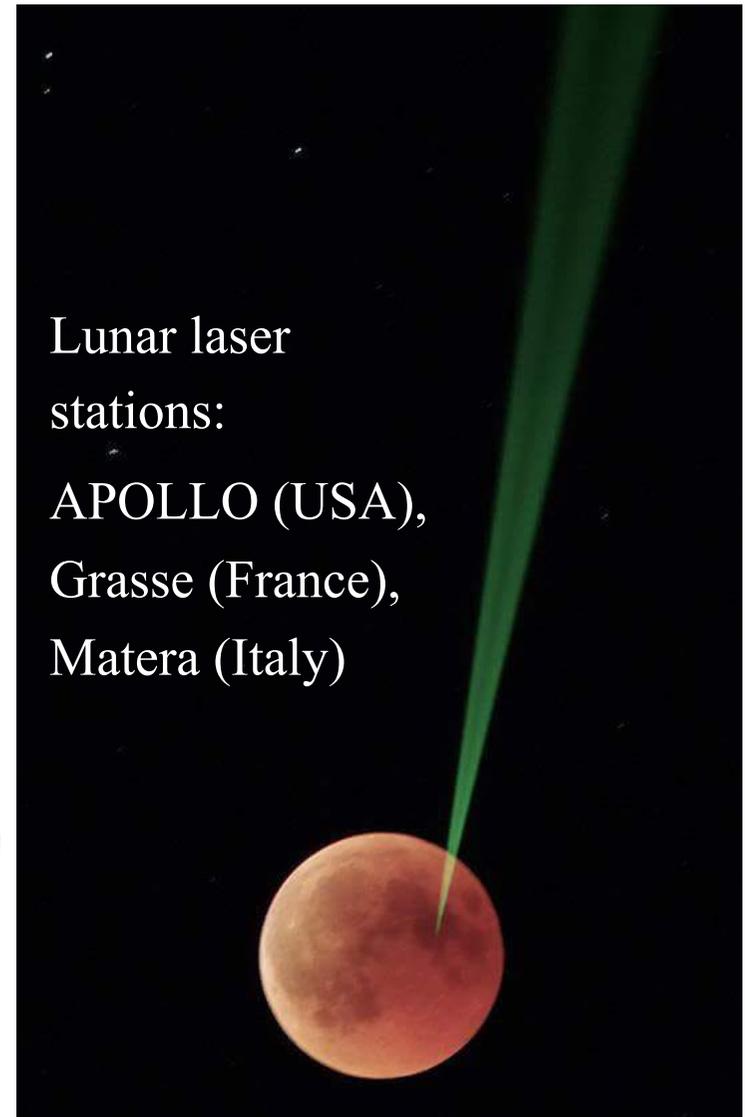
- Italian ASI-INFN Joint Lab on laser retroreflector and ranging
- Lunar Laser Retroreflectors (LSITP, ESA)
- Asteroid (Didymos/Hera) and Comets
- Phobos and Deimos
- Prospects

Accurate Time of Flight (ToF)  
of short laser pulses, timed by  
accurate ground atomic clocks

Right: LLR during lunar eclipse of  
July 28, 2018 from ASI-Matera



Lunar laser  
stations:  
APOLLO (USA),  
Grasse (France),  
Matera (Italy)

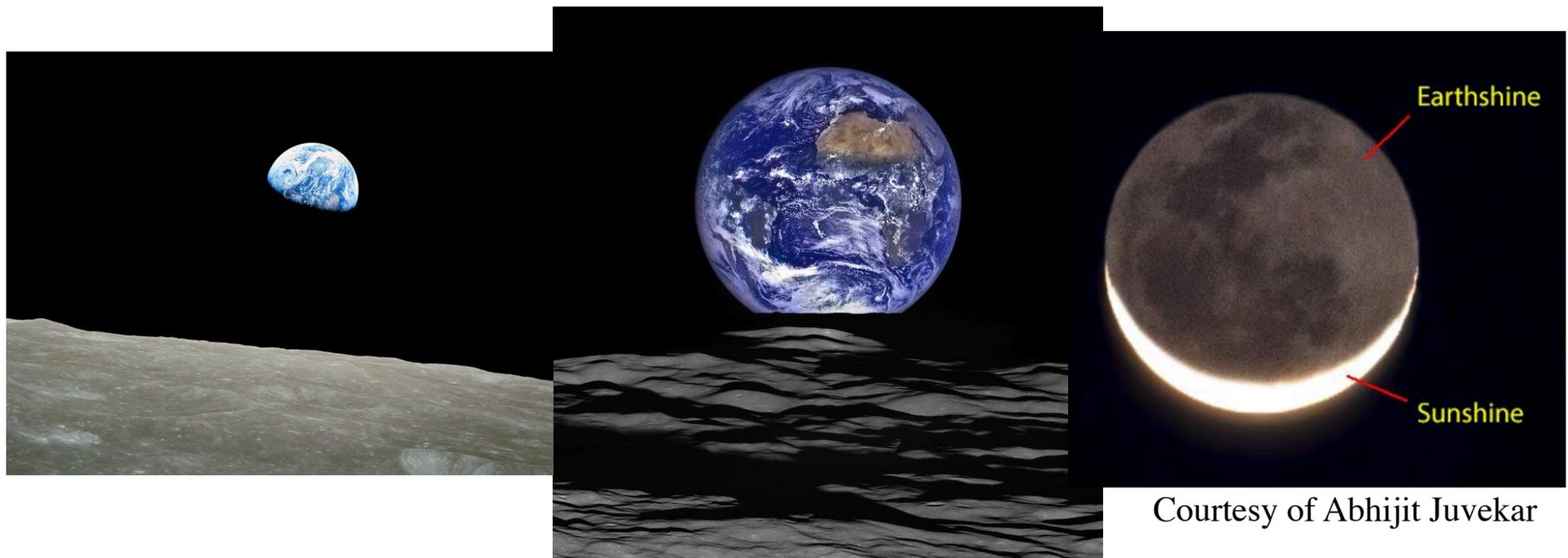


## Earthshine (*Leonardo da Vinci*, 500 years later)

**Earthrise:** 1968, Apollo 8 (left) vs. 2018, LRO (middle)

**Earthshine:** first explained by Leonardo da Vinci in the 1500s (right)

April 2019 is the 500<sup>th</sup> anniversary of Leonardo's death



Courtesy of Abhijit Juvekar

# ASI-INFN Joint Lab on Laser Retroreflectors & Ranging

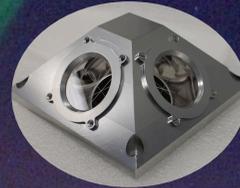
ASI – INFN– Ministry Foreign Affairs  
collaboration with USA partners:  
**NASA, Universities, USGS,**  
**NOAA-NIC, USA space industries**



Comet/asteroid  
**NASA-SSERVI**

**ASI – Matera  
Laser Ranging  
Observatory**

LAGEOS  
**NASA-GSFC**



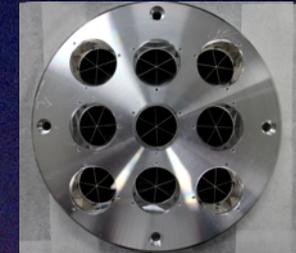
Earth  
Observation  
**USGS, NOAA**



Moon  
**U. Maryland,  
U. San Diego,  
Industries,  
NASA-SSERVI**



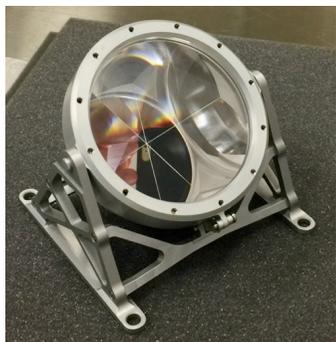
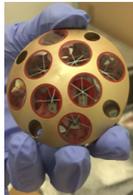
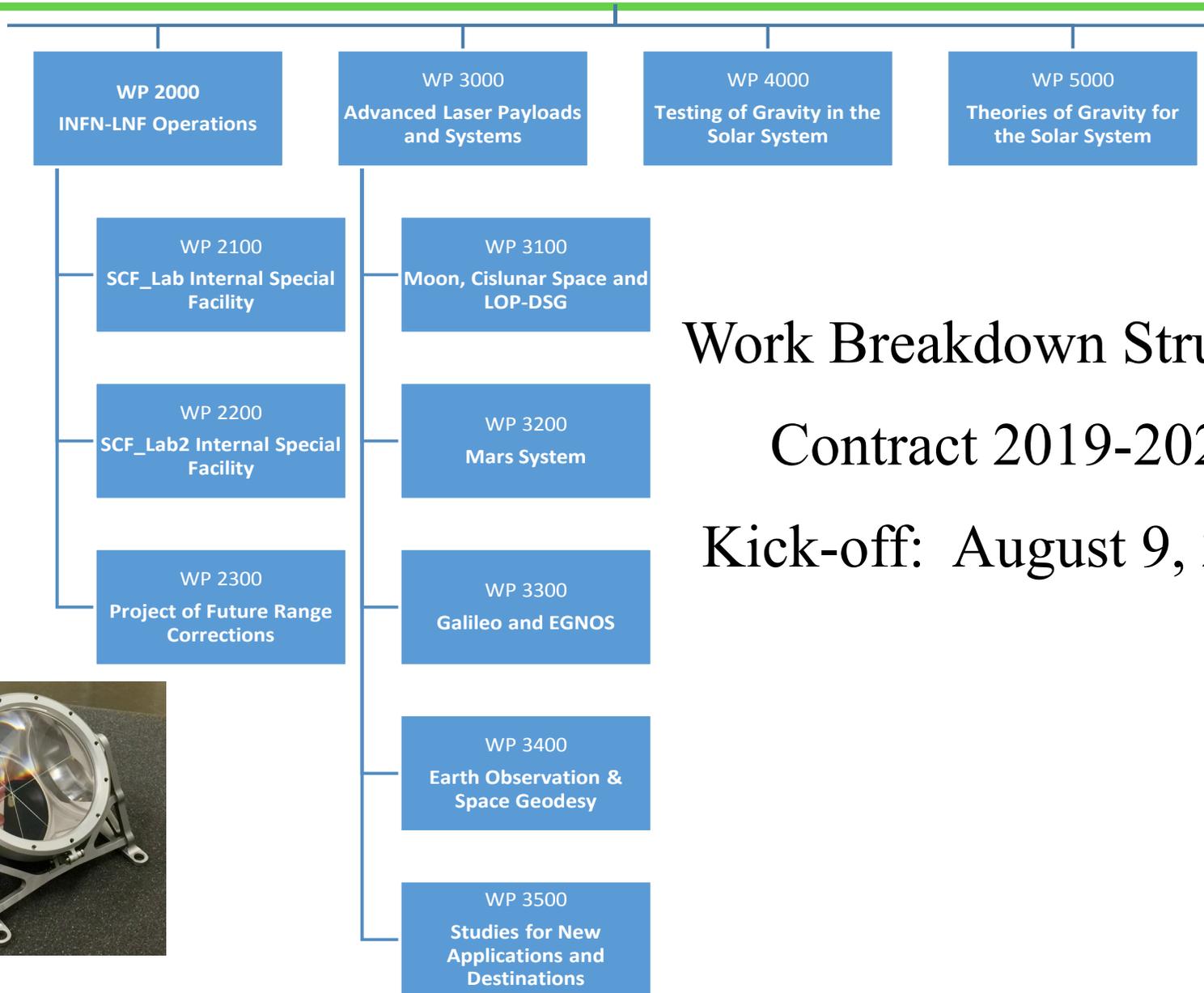
Mars, Moon;  
Europa?  
**NASA-JPL**



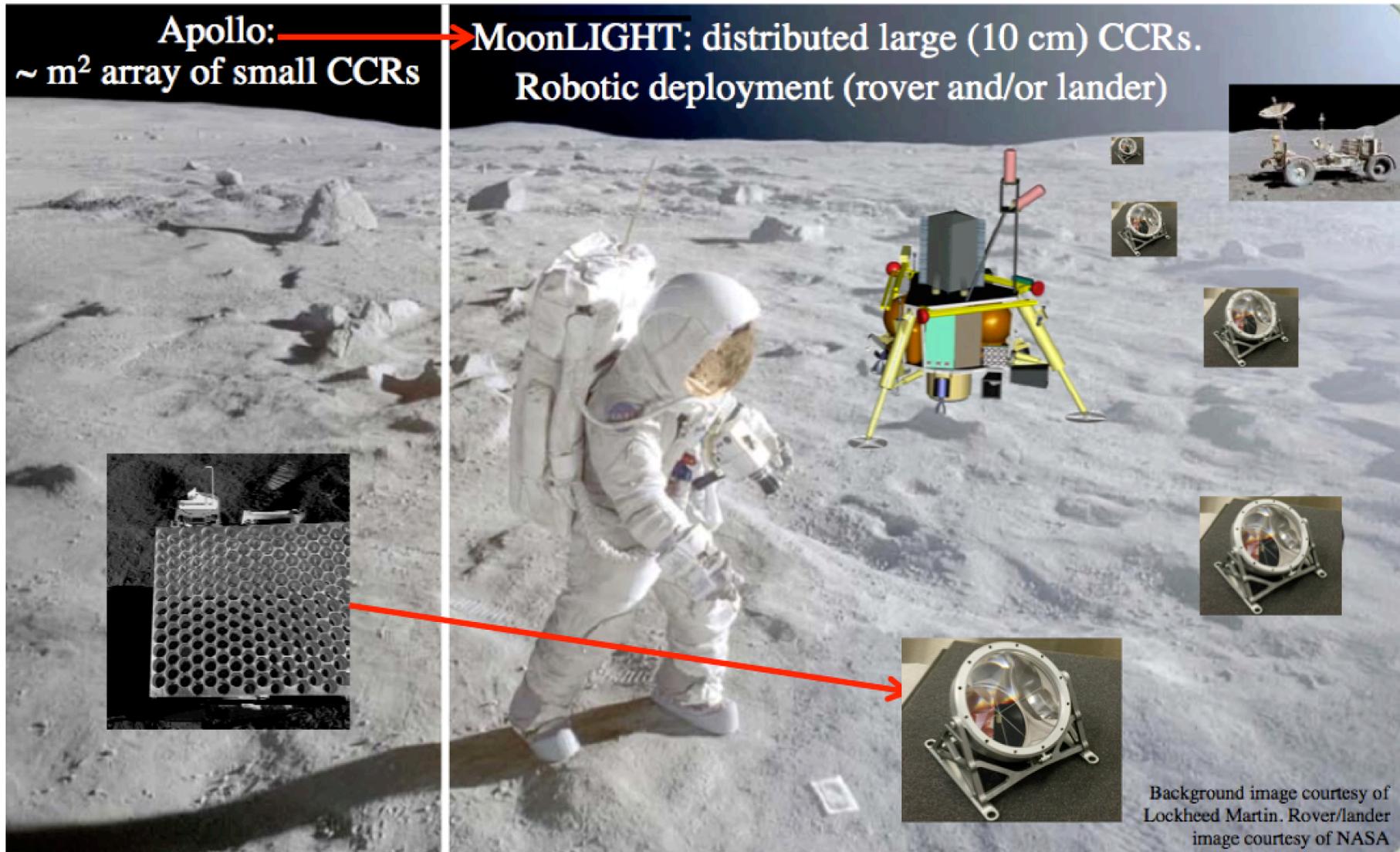
Phobos/Deimos  
**NASA-SSERVI**

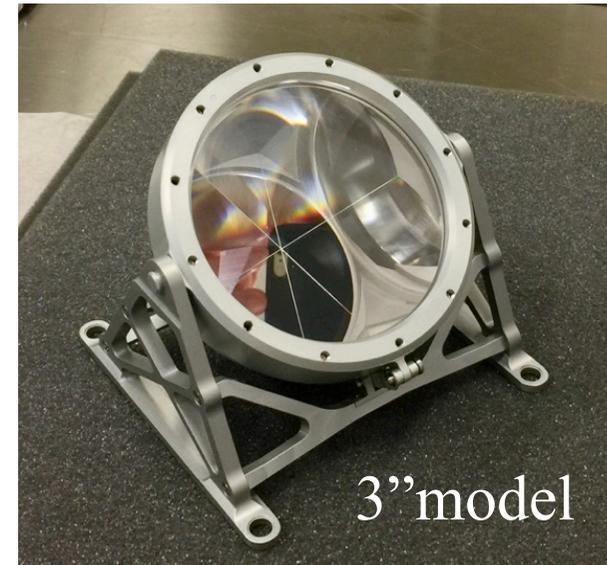
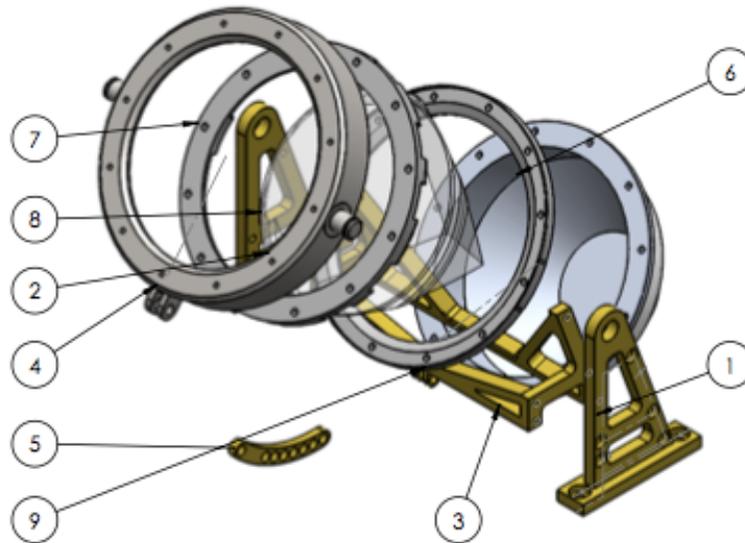


Galileo,  
GNSS



Work Breakdown Structure  
 Contract 2019-2024  
 Kick-off: August 9, 2019





**Microreflector** ~5 cm, 25 gr  
(for Ceres Robotics minirover,  
Michael Sims PI)





- Big, single laser retroreflector observed from Earth
  - Italy/US: **MoonLIGHT** = Moon Laser Instrumentation for General relativity High accuracy Tests
- Miniaturized retroreflector observed from orbiters
  - **microreflectors** suited for landing-roving investigations on the Moon, Mars (& other airless solar system bodies)
- Orbital, positioning SW
  - **PEP** (Planetary Ephemeris Program) for Moon/Mars positioning: developed since 1960/70s at the Harvard Smithsonian Center for Astrophysics (CfA), by Shapiro, Reasenberg, Chandler (now at UCSD, with T. Murphy)

- LLR provided the best data for the deep interior of the moon. Complementary to the analysis of NASA GRAIL and other orbiter missions, which measure from the crust down
  - ✓ In 1998, analysis of the LLR data discovered and measured the size, shape and dissipation of the liquid core of the Moon (Williams et al)
  - ✓ Confirmed by re-analysis of Apollo Seismometry (Weber et al 2011)
- Next-Gen reflectors will increase/improve this consolidated synergism for better understanding the lunar interior
  - ✓ By allowing for more accurate data, from more stations of the International Laser Ranging Service (ILRS, part of IAG)
- Lunar Geophysical Network (LGN):
  - ✓ Core instruments: seismometer, heat flow probe, retroreflector, ...
  - ✓ Single/large retroreflectors ‘baselined’ for >10 years
  - ✓ Proposal for 4-stations/lander LGN to NASA NF-5 (C. Neal PI)
  - ✓ ESA: start with single geophysical nodes & missions of opportunity

Improvements of space segment up to  $\times 100$  with MoonLIGHTs plus current LGN of Apollo/Lunokhods



Science measurement / Precision test of violation of General Relativity	Apollo/Lunokhod * few cm accuracy	MoonLIGHTs **	
		mm	sub-mm
Parameterized Post-Newtonian (PPN) $\beta$	$ \beta - 1  < 1.1 \times 10^{-4}$	$10^{-5}$	$10^{-6}$
Weak Equivalence Principle (WEP)	$ \Delta a/a  < 1.4 \times 10^{-13}$	$10^{-14}$	$10^{-15}$
Strong Equivalence Principle (SEP)	$ \eta  < 4.4 \times 10^{-4}$	$3 \times 10^{-5}$	$3 \times 10^{-6}$
Time Variation of Gravitational Constant	$ \dot{G}/G  < 9 \times 10^{-13} \text{yr}^{-1}$	$5 \times 10^{-14}$	$5 \times 10^{-15}$
Inverse Square Law (ISL) - Yukawa	$ \alpha  < 3 \times 10^{-11}$	$10^{-12}$	$10^{-13}$
Geodetic Precession	$ K_{gp}  < 6.4 \times 10^{-3}$	$6.4 \times 10^{-4}$	$6.4 \times 10^{-5}$

\* J. G. Williams et al. PRL 93, 261101 (2004)

\*\* M. Martini and S. Dell'Agnello, R. Peron et al. (eds.),

DOI 10.1007/978-3-319-20224-2\_5, Springer Intern. Publishing, Switzerland (2016)

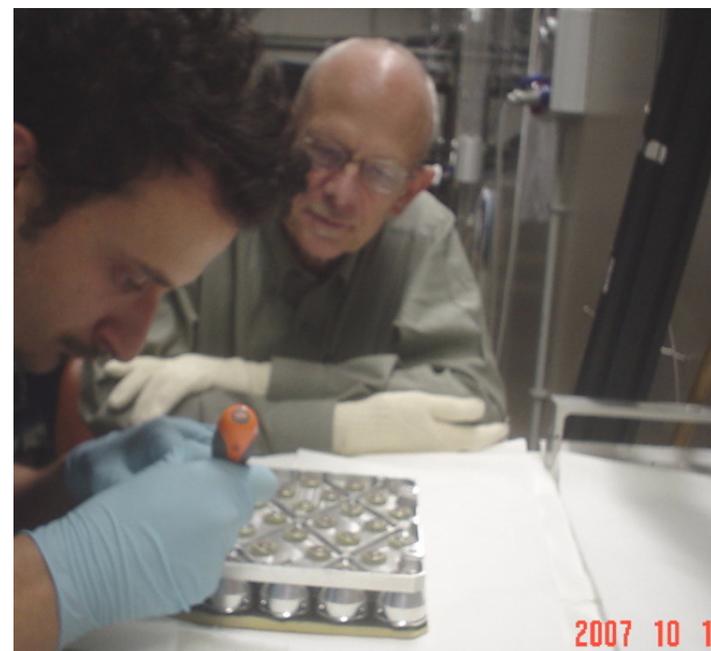


# July 2, 2019: Next-Gen Lunar Reflector selected by NASA for LSITP



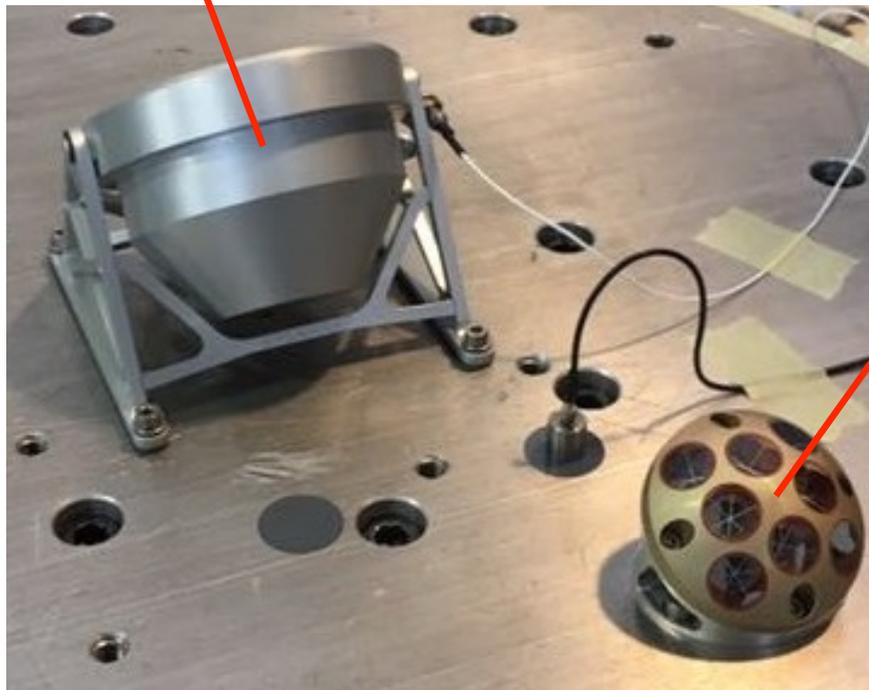
PI = D. Currie of U. of Maryland  
Co-PI group = SD & INFN

“... target for lasers on Earth to  
precisely measure the Earth-Moon  
distance ... and address questions  
of fundamental physics.”

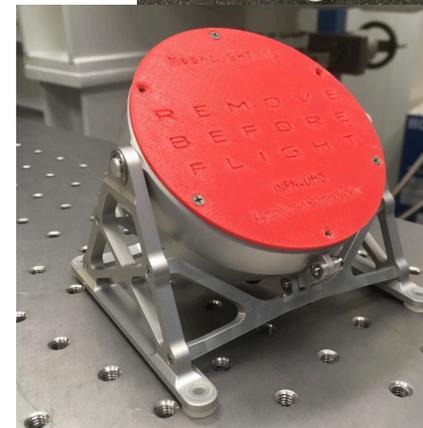


- Qualifications (even RBF) at end of 2017
- Big reflector of 3 inch (pictured, ~500 gr) instead of 4 inch (~1.3 kg), due to GLXP weight and cost limitations
- Exclusive FOVs to Earth and to lunar orbit

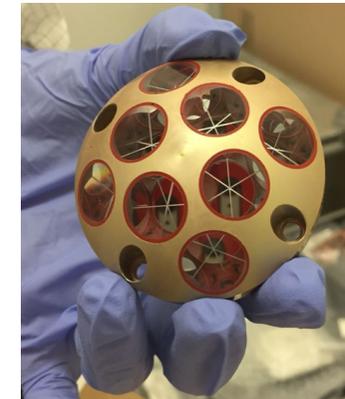
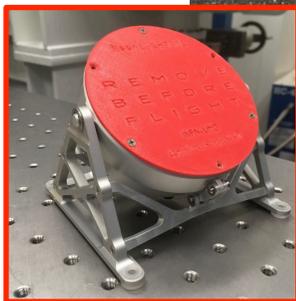
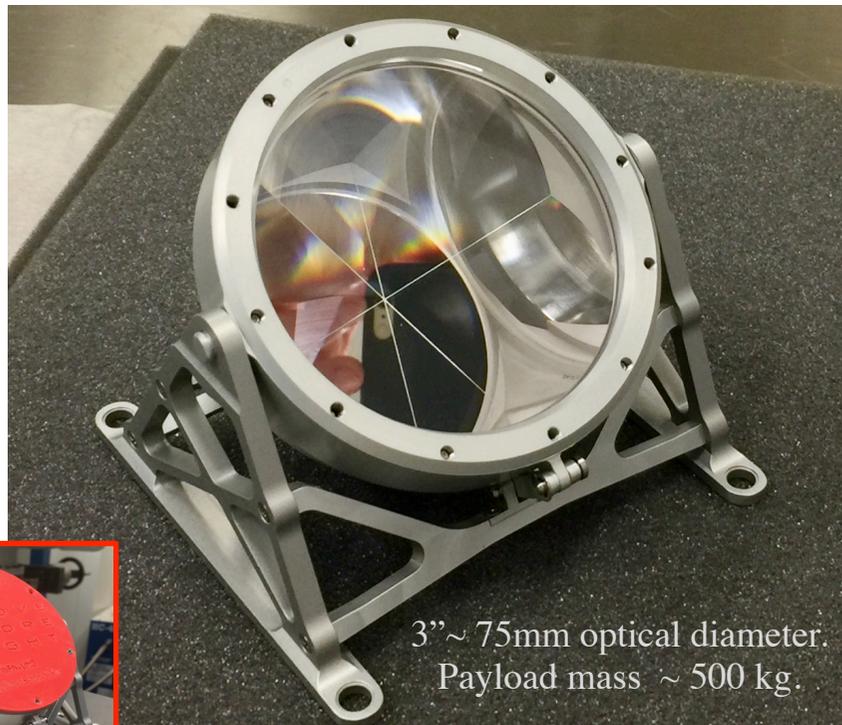
To Earth



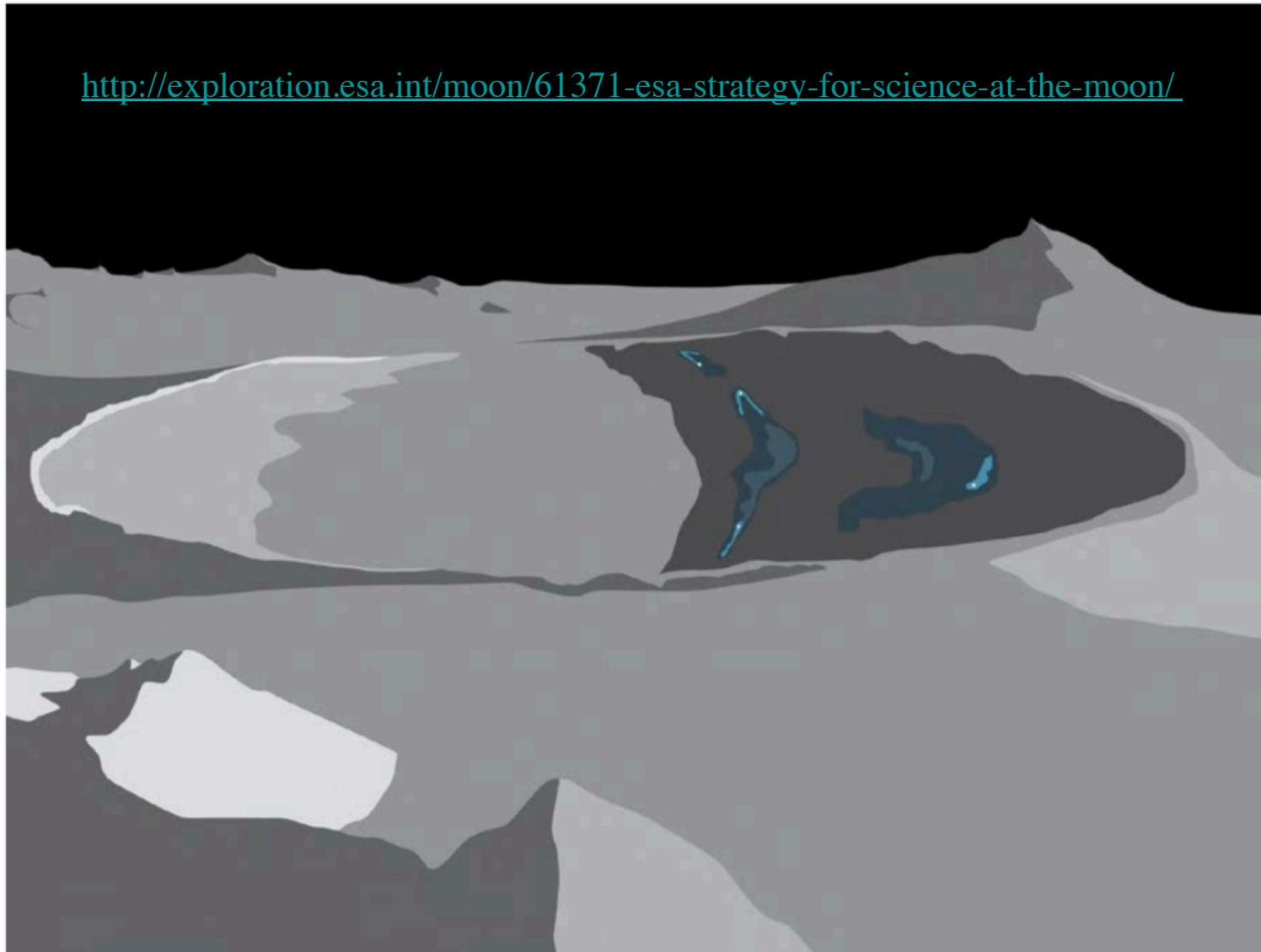
To lunar orbit



- L1 closer than Moon surface
- Therefore GLXP big reflectors of 3 inch (left photo) very well suited
- Mars/Moon microreflector well suited for s/c tracking and docking

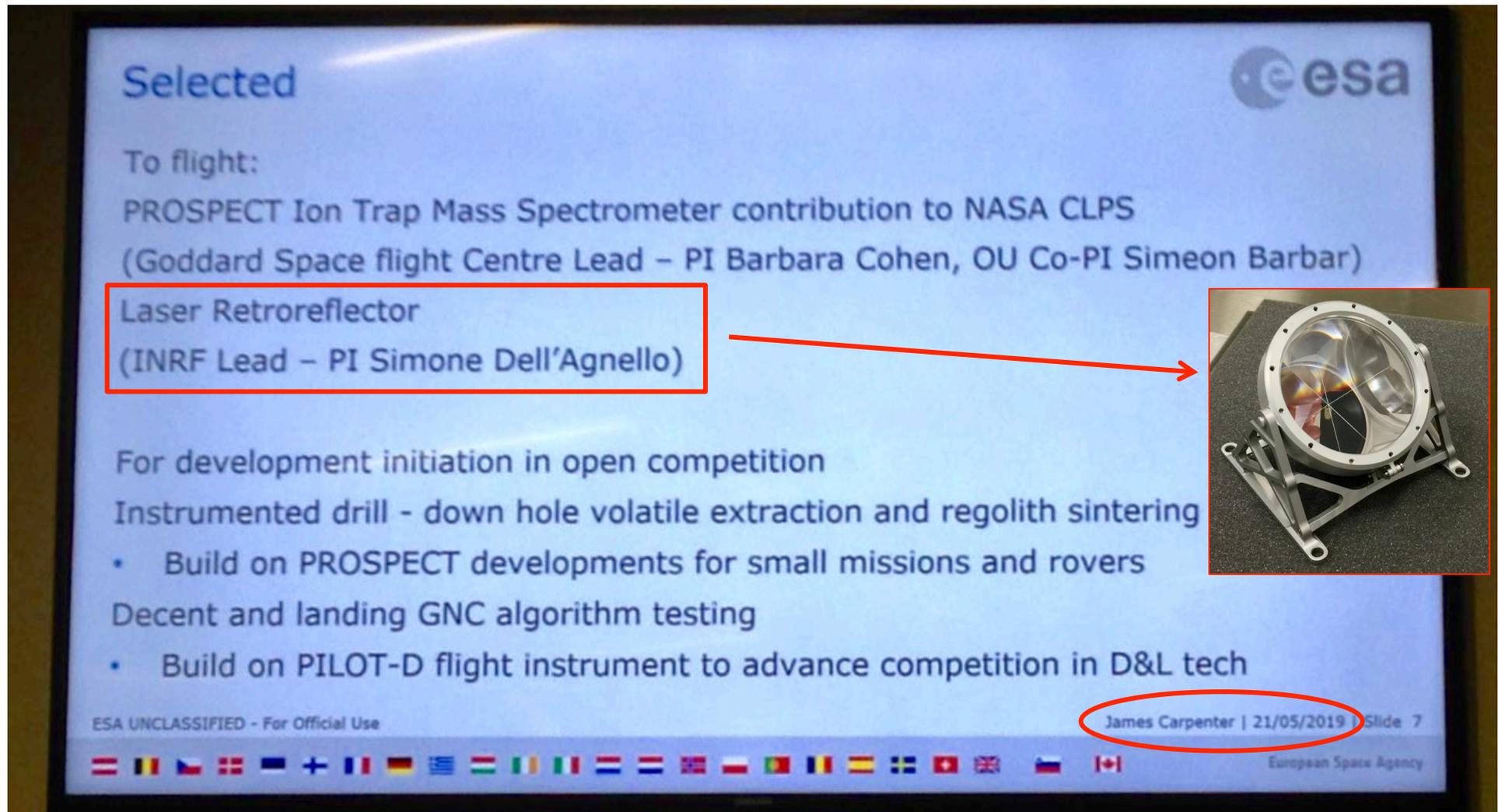


# ESA Strategy for Science at the Moon



# May 2019: big reflector **selected by ESA** for lunar mission of opportunity in 2021

ESA-INFN contract for reflector **with accurate active Earth pointing!!**



The slide is titled "Selected" and features the ESA logo in the top right corner. It lists several mission contributions:

- To flight:
  - PROSPECT Ion Trap Mass Spectrometer contribution to NASA CLPS (Goddard Space flight Centre Lead – PI Barbara Cohen, OU Co-PI Simeon Barbar)
  - Laser Retroreflector (INRF Lead – PI Simone Dell’Agnello)**
- For development initiation in open competition
  - Instrumented drill - down hole volatile extraction and regolith sintering
    - Build on PROSPECT developments for small missions and rovers
  - Decent and landing GNC algorithm testing
    - Build on PILOT-D flight instrument to advance competition in D&L tech

A red box highlights the "Laser Retroreflector" entry, with a red arrow pointing to a photograph of the physical device. The photograph shows a complex, metallic, spherical instrument with a central lens and a base. At the bottom of the slide, the text "James Carpenter | 21/05/2019 | Slide 7" is circled in red. The slide also includes the text "ESA UNCLASSIFIED - For Official Use" and a row of European Union member state flags.

Activity	Approach
Determine ages of basins and young lavas	Sample return from locations with diverse ages based on crater counting
Characterise the internal structure and thermal state of the lunar interior	Seismometers, heat flow probes, and laser retroreflectors at one or multiple locations (network)
Characterisation of polar volatiles	Surface and subsurface in situ measurements, diverse locations, eventual sample return
Diverse sampling of mare basalts	Near side diverse locations, sample return and in situ measurements, mineralogy, chronology, and composition
Identification and sampling of palaeoregolith deposits trapped between lava flows	Deep drilling and sample return

*Table 4 – Science of the Moon: research activities and approaches.*

Topic	Approach
Assess survivability of organisms and microorganisms	Identify, visit, and sample crash sites of Apollo LM ascent stages, biological growth and exposure experiments
Test ISRU feasibility	Extract water from PSRs, extract oxygen from regolith, sinter regolith, metal production
Test General Relativity	Deploy <b>laser retroreflectors</b> at diverse locations
Physiology in the lunar environment	Representative biological models and human subjects at the lunar surface

*Table 6 – Science on the Moon: topics and research approaches.*

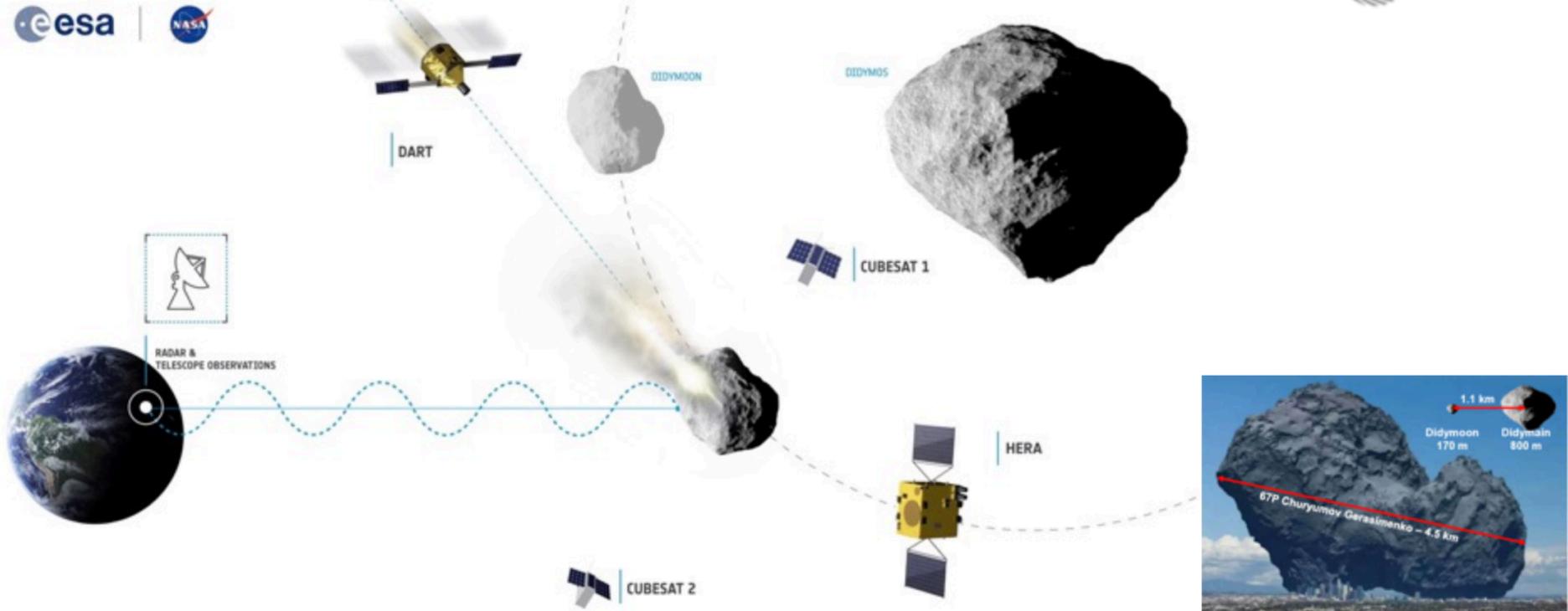
- Passive, 50-year lifetime, laser retroreflector-based  
Lunar Geophysical Networks (LGN)
  - NASA LSITP: single big lunar reflector with fixed pointing
  - ESA selection: single big lunar reflector with **active** pointing
  - Microreflector (nano & pico versions also available)
  - Future LGN proposal for New Frontiers (C. Neal PI)
- Lunar surface geodesy and deep lunar interior
- Accurate test of General Relativity (and beyond)
- Georeference exploration (landing site, roving) & ISRU
- Lunar commerce: L1, LOP-G, surface ... (ISRU)

Courtesy of I. Carnelli (ESA)



Courtesy of I. Carnelli (ESA)  
AIDA: DART (NASA), Hera (ESA)

## AIDA international collaboration with NASA



“kinetic impactor” validation requires impactor (NASA/DART) + observer spacecraft (ESA/Hera) to retrieve all physical and dynamical parameters of asteroid Didymos necessary to validate numerical impact codes



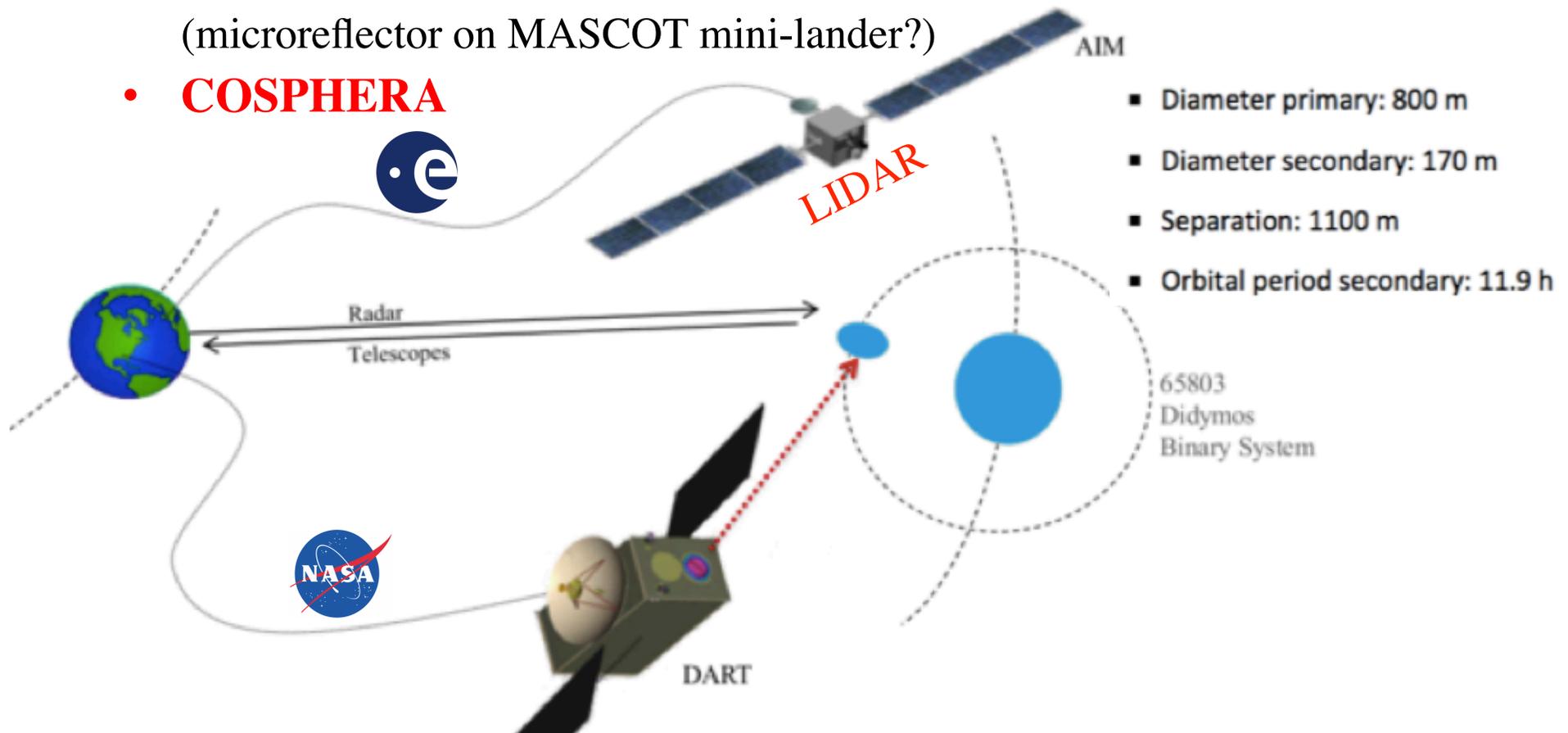
European Space Agency

Hera: proposed ESA mission (~2023)

DART (Double Asteroid Redirect Test), approved NASA mission

ASI-INFN laser microreflectors support observations by Lidar on Hera:

- **Micro/nano/pico-reflectors** on two 6U CubeSats released by Hera  
(microreflector on MASCOT mini-lander?)
- **COSPHERA**

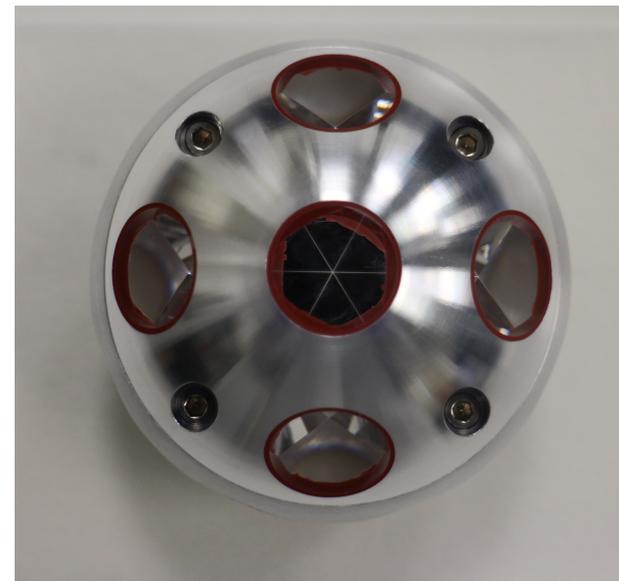


**COSPHERA = COmet/asteroid SPHERical micro-Reflector Array**  
Passive, very small/light, omnidirectional, lifetime of decades

HERITAGE: NASA InSight, ESA/ASI ExoMars

Laser tracking supports retrieval, redirection (ion deflection, LAP ...), laser-guide ...

**Prototype: 18 ½" microreflectors, < 100 gr, ~5 cm size**



# Laser positioning of Didymoon

- Mars microreflector on MASCOT-2
  - ✓ Weight  $< 2 \times 10^{-3}$  of MASCOT-2 mass
- COSPHERA, landed/dropped separately

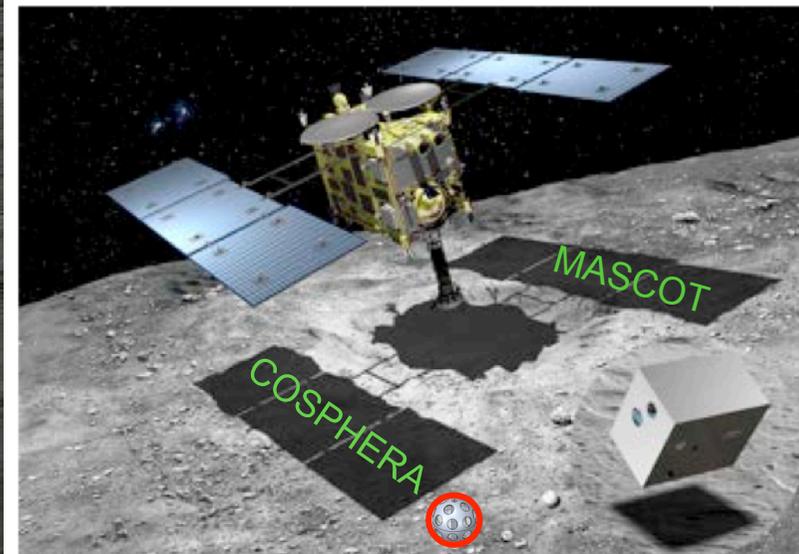
Mars Microreflector



MASCOT, a Mobile Asteroid Surface Scout

COSPHERA

Lidar on Hera  
MASCOT by DLR  
COSPHERA by INFN



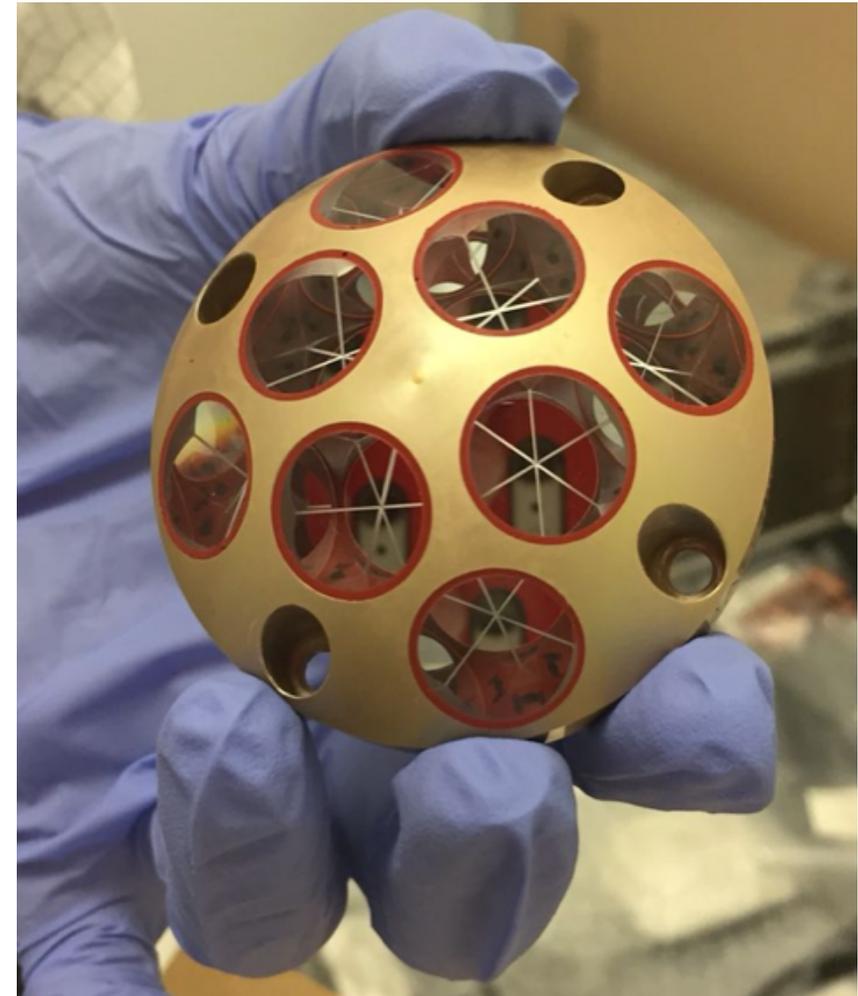
Artist's conception of HY-2 during sampling, also showing MASCOT landed on the surface. CREDIT: JAXA/Akihiro Ikeshita.

(COSPHERA size no to scale)

## Didymos



## Mars/Moon

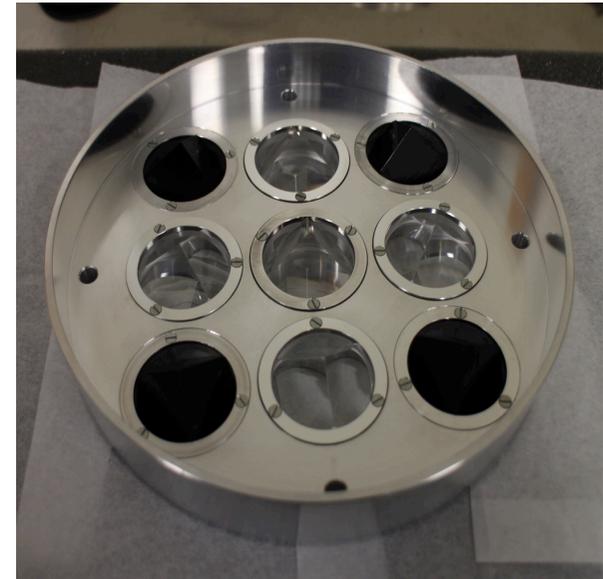
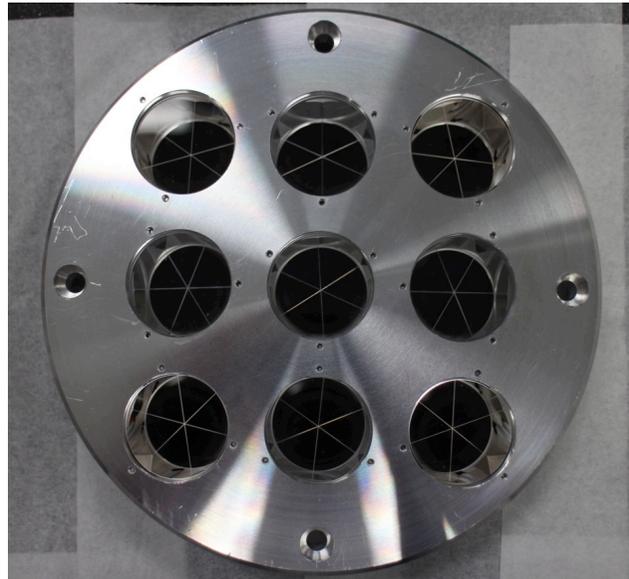


# nano-reflector (left), pico-reflector (right)



- **PANDORA: Phobos AND Deimos laser Retroreflector Array**
- Reconstruct Phobos-Deimos orbits → Focus of orbit is the Mars center of mass → Test of General Relativity at 1.5 AU from Sun
  - PPN  $\gamma$  (spacetime curvature)
  - PPN  $\beta$  (strong equivalence principle)
  - $\dot{G}/G$  (gravitational constant)
- PEP (Planetary Ephemeris Program) orbital SW

- PANDORA designed/built/tested for observation by Mars orbiters
- Subgroups of reflectors with custom specs, to ensure laser return at varying distances and velocities of the orbiter



- Mission opportunity: Mars Moon eXplorer (MMX) of JAXA, with the collaboration of NASA and DLR
- PANDORA installed on landers/rovers
  - Additional option: COSPHERA directly released on Phobos/Deimos

E. Law's group (JPL) and B. Day (SSERVI)

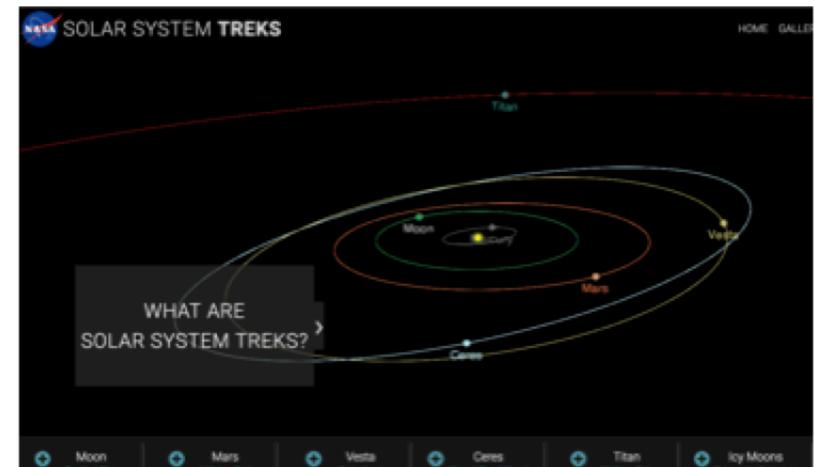


Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

## Solar System Treks Project (SSTP)

- An element of NASA's Solar System Exploration Research Virtual Institute (SSERVI) with software development and operations done at JPL
- Supporting NASA missions and NASA collaborations with partnering agencies
- A family of interactive web-based Trek portals
  - Mission Planning
  - Scientific Research
  - Public Outreach/STEM

<https://trek.nasa.gov>



E. Law's group (JPL) and B. Day (SSERVI)



## LRR/LLR Geometry Calculator

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In collaboration with investigators from INFN-LNF and UMCP, the SSTP team is currently developing the LRR/LLR Geometry Calculator that will:

- Support planning for future LRR deployment and LLR research on lunar cartography, lunar interior and precision tests of general relativity
- Enable prediction of relative geometries between Earth laser stations, LRRs, LRO (and similar future orbiters), and the Sun
- Identify NAC images showing reflections of the Sun or lasers off of LRRs

# ASI-INFN Joint Lab on Laser Retroreflectors & Ranging

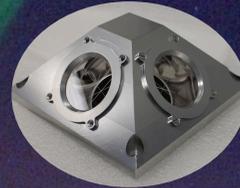
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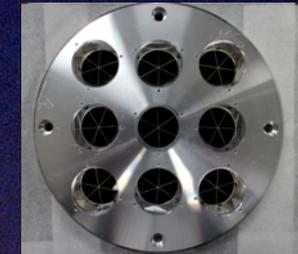
Earth  
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